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THE AEROPHYSICS DEPARTMENT
Of
MISSISSIPPI STATE UNIVERSITY

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An Experimental Investigation of Fillet Design
For Application to Airship Fins

By

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LIST OF FIGURES

LIST OF SYMBOLS

α	— Angle of attack with reference to aircraft longitudinal axis--degrees (Add 3.92 degrees for wing angle of attack)
X	— Distance from leading edge of wing at fuselage wall--inches
τ	— Skin friction or surface shearing stress--pounds per square foot
p	— Local static pressure--pounds per square foot or inches of water
H	— Total pressure--pounds per square foot or inches of water
q	— Dynamic pressure--pounds per square foot or inches of water
U	— Velocity parallel to surface outside the boundary layer--feet per second or miles per hour
c	— Wing chord--inches or feet
V	— Suction velocity--feet per second
θ	— Momentum thickness--feet
C_p	— Static pressure coefficient--dimensionless
C_Q	— Suction flow coefficient--dimensionless
C_{p_t}	— Suction pressure coefficient--dimensionless
$C_Q C_{p_t}$	— Total suction power coefficient--dimensionless
C_{D_w}	— Total drag coefficient measured from wake profiles--dimensionless
C_f	— Local skin friction coefficient--dimensionless
C_F	— Total skin friction coefficient--dimensionless
Q	— Suction flow quantity--cubic feet per second

Note: Subscript (o) denotes freestream conditions.

INTRODUCTION

Prior to the present investigation, a study of an airship in flight having Mylar tapes or tufts attached to the fins and after-portions of the envelope was made. This study revealed a region of separated flow near the intersection of the fin leading edge with the envelope.(Figure 1, Reference 2). Regions of weak boundary layer flow were detected which extended along the entire length of the fin-envelope intersections. During turns, flow separation also occurred on the outboard side of the deflected control surfaces as well as on the extreme rear portion of the envelope aft of the control surfaces.

As a result of these findings, the Aerophysics Department of Mississippi State University proposed the use of fabric tension-field fillets with suction boundary layer control for improvement of the flow conditions about the airship fins and control surfaces. These fillets would eliminate local separation near the fin leading edge, and reduce momentum losses in the boundary layer along the fin-envelope intersections. Suction air would be exhausted along the lower hinge-line of the control surfaces in order to accelerate the flow within the boundary layer in this region, and thus delay turbulent separation. Such an installation would then result in a reduction of pressure drag and improved control response of the airship.

The characteristics of the flow along the fin-envelope intersections of the airship are typical of those occurring along similar intersections in the presence of an adverse pressure gradient. It was, therefore, possible to utilize the wing-fuselage intersections of an AT-11 aircraft to further investigate the advantages of filleted intersections. A flight test program was initiated and two fillet configurations were tested.

The primary purpose of this investigation was the development of a low-drag fillet configuration using suction boundary layer control. An analysis and discussion of the results of the investigation are presented herein.

TEST PROCEDURE AND APPARATUS

Test Program:

The two fillet installations investigated will be referred to as fillets "A" and "B" throughout this report. The two configurations are shown in figures 2 and 3.

The flight test program was conducted as follows:

Phase I--A study of flow phenomena along the port wing-fuselage intersection of the aircraft.

Phase II--Testing of fillet "A" installed along the starboard wing-fuselage intersection.

Phase III--Testing of fillet "A" with suction boundary layer control.

Phase IV--Testing of fillet "B" installed along the port wing-fuselage intersection.

Fillet Design:

Fillet "A" was basically a constant-radius type fillet with a rounded trailing edge that was blended into the fuselage. After analysis of the data obtained from tests of fillet "A", fillet "B" was designed. This fillet was tapered from a small leading edge radius to a wide, shallow surface at the trailing edge of the wing. Length of fillet "B" was extended beyond that of fillet "A" for improvement of pressure recovery.

Both fillets were of Fiberglas construction with surfaces sanded to a smooth finish.

Tests:

Tests were conducted at altitudes below 10,000 feet and data reduced to sea level conditions. Measurements included pressure distributions, wake surveys, tuft observation and photography, and skin friction measurements.

Flight in calm air was stable, allowing duplication of tests with little variation in results. It was necessary to fly the aircraft in single engine flight so that propeller slipstream effects would not seriously affect the measurements. The engine adjacent to the intersection where measurements were being made was idled, rpm being adjusted so that the total pressure immediately behind the propeller was equal to that of the free-stream. Propeller effects were thus minimized, but some error was undoubtedly included in the measurements due to the idling propeller.

Instrumentation:

Pressure readings were taken in inches of water from a test panel consisting of 24 pressure gauges. The aircraft was equipped with a calibrated Kollsman airspeed indicator and a mechanical type angle of attack indicator.

Both fillets were equipped with static pressure orifices connected to the test panel by pressure tapes. Pressure distributions were taken along the wing-fuselage intersection by a thin pressure tape attached to the skin of the aircraft.

Preston-type shear meters were used to measure the frictional drag of the fillet surfaces. Measurements were made along the centerline and both edges of the fillets since shearing stress varied across the width of each fillet.

Photographs of the fillets with tufts attached were taken with a 35 mm. camera mounted several feet aft of the trailing edge of each fillet.

A wake rake, 22 inches in length, was used for wake survey measurements. This rake consisted of 19 total pressure tubes and 5 static pressure tubes. The rake was hinged to the fuselage wall and could be rotated to any desired angle within the wake.

Suction System:

Suction air to fillet "A" was supplied by a centrifugal aircraft supercharger driven by a two-cycle gasoline engine. The installation was located just behind the pilot's compartment, the supercharger being ducted directly into the fillet through the fuselage wall. A calibrated venturi was used to determine suction flow quantity and internal fillet pressure was measured from static pressure tubes installed along the inner fuselage wall.

REDUCTION OF DATA

Tuft observations of fillet "A" at aircraft attitudes ranging from level flight to the stall condition revealed extensive wing-root separation at angles of attack greater than 5 degrees. (Figure 4). Since flow was completely attached at lower angles of attack, tests were restricted to angles of attack greater than 5 degrees.

Additional photographs of the port wing-fuselage intersection and both fillets were taken from a position aft of the fillets in order to study flow conditions over the rear portions of the fillets and intersection.

Wake surveys of each fillet and the port wing-fuselage intersection were made to determine the relative drag and to compare flow patterns behind each installation. Drag was calculated from total and static pressures within a plane described by a rotating wake located approximately 4 feet aft of the wing trailing edge. Total head pressure measurements within the plane of measurement for the wing-fuselage intersection with and without fillet "B" are illustrated in Figure 11.

Wake drag was computed by integration of the measurements taken within the plane of measurement described by the rake. Integration was performed using Jones' relation:

$$D_w = q_0 \iint 2\left[g - \left(\frac{P_1 - P_0}{q_0}\right)\right]^{\frac{1}{2}}\left[1 - g^{\frac{1}{2}}\right] dS_1$$

where $g = \left[1 - \left(\frac{H_0 - H_1}{q_0}\right)\right]$, and dS_1 is an element of area in the plane of measurement. (Reference 3).

Suction parameters were expressed in non-dimensional form as follows.

Suction flow coefficient $C_Q = \frac{Q}{U_o c^2}$.

Total suction pressure coefficient $C_{P_t} = \frac{H_o - P_{int}}{q_o}$, where P_{int} = fillet internal pressure.

The expression $C_Q C_{P_t}$ must be subtracted from the drag coefficient of fillet "A" with suction boundary layer control in order to account for the power expended for suction.

Suction velocity for fillet "A" was computed from the following equation,

$$V = 3.5\ \theta_i U_i \frac{dU/dX}{U} - \frac{1}{2} C_{f_i} U$$

(Reference 4)

where the subscript (i) denotes conditions at the first row of suction holes. This equation was evaluated from measurements made of fillet "A" at an angle of attack of 12 degrees. Suction began approximately 3 feet from the wing leading edge and extended to the trailing edge of the fillet. Numerous modifications were made to the initial suction distribution with only moderate improvements noted in the final results.

DISCUSSION OF RESULTS

A comparison of drag coefficients of the port wing-fuselage intersection and the starboard intersection with fillet "A" installed was made. Results showed that fillet "A" increased rather than decreased the intersection drag. (Figure 13). This increase amounted to approximately 22 per cent at an angle of attack of 5 degrees, decreasing at higher angles of attack. It was apparent that unless suction boundary layer control could be used to effectively reduce the drag of fillet "A" below that of the unfilleted intersection, this configuration would be unsatisfactory for use on airship fins.

Tests with suction boundary layer control resulted in only modest reductions of drag, however. Maximum drag decrease was approximately 6 per cent. Addition of suction power coefficients to wake drag coefficients offset this small drag decrease so that no overall gain was made. Failure of the suction system to significantly reduce the drag of the intersection was primarily due to the restriction of suction area by the narrow width of the fillet toward the trailing edge of the wing. Attachment of the separated flow over the rear portions of the fillet could not be achieved because of turbulence and cross flow from the wing and fuselage. Figures 8 and 9 show the severe flow conditions which existed on the wing and flap adjacent to the fillet. These conditions were improved in later tests with fillet "B," a fillet of improved design.

An analysis of the data obtained during the first three phases of the investigation was made before attempting the design of an improved fillet configuration. The high drag of fillet "A" was largely attributed to an increase of pressure drag over that of the unfilleted intersection. A comparison of the pressure distribution of the wing-fuselage intersection before and after the installation of this fillet shows the disadvantage of the constant-radius type fillet. (Figures 5 and 6). The large fillet radii cause increases in supervelocity and correspondingly higher negative pressures over the forward portion of the fillet. A more severe adverse pressure gradient is created which causes early separation and results in less pressure recovery.

A study of tuft activity also revealed poor flow conditions along the length of fillet "A." (Figures 8 and 9). Turbulent separation occurred on the rear portions of the fillet at all angles of attack above 5 degrees. Suction improved the flow forward of the flap hinge-line, but failed to attach the flow aft of this position.

It is of interest to compare the above conditions with those of the unfilleted intersection illustrated in Figure 7. The flow along the intersection is typical of corner flow in an adverse pressure gradient, and is similar to that of the fin-envelope intersections of the airship. Actual separation of the flow along the corner is not severe, but the boundary layer is thickened and retarded by interaction of the fuselage wall and wing boundary layers. The thickened boundary layer of the corner results in poor pressure recovery and high pressure drag. Tufts along the corner which lie in the retarded flow show little activity due to the weak flow near the surface.

Fillet "B" was designed for improved pressure recovery by extending the fillet length 14 inches beyond that of fillet "A." The fillet was tapered from a small leading edge radius to a broad, flattened trailing edge. Fillet radius was determined from velocity profile measurements made along the corner of the port wing-fuselage intersection. Contour of the fillet surface corresponded closely to the heights of the velocity profiles measured along the intersection.

Tuft observations revealed that flow was much improved along the port wing-fuselage intersection after installation of fillet "B." Although highly turbulent, the flow appeared to be fully attached at high angles of attack. Improvements were also noted in the flow on the wing and flap along the outboard edge of the fillet. (Figure 10).

Pressure recovery was less than expected but improved over that of both fillet "A" and the unfilleted intersection. (Figures 5 and 6). Improvement was more evident at the higher angles of attack.

Due to the above improvements, subsequent measurements of the intersection with fillet "B" revealed substantial reductions of drag. Maximum drag decrease of the intersection due to fillet "B" was 49 per cent at an angle of attack of 9 degrees. (Figure 13).

Measurements of shearing stress along each fillet were made in an attempt to approximate the percentage of wake drag due to skin friction. These measurements showed higher shearing stresses over the entire length of fillet "B," indicative of higher velocities within the boundary layer along the length of this fillet. (Figure 14). The shearing stress curve of fillet "B" also indicated separated or nearly separated flow at the trailing edge of the wing and attached flow aft of this position. In every position, however, flow was improved over that of fillet "A."

Total frictional drag of the two fillets was found to be approximately the same after integration of the shearing stress measurements. (Figure 15) It should be noted that the friction drag coefficients appear small when compared to the wake drag coefficients of Figure 13. This is because frictional losses from the underside of the wing as well as those from the upper wing and fuselage wall are included in the wake measurements.

Likewise, a large component of the wake drag is due to pressure drag of the intersection. Allowing for these considerations, it would appear that the total friction drag component of the wake drag is small, being on the order of 20 per cent of the total measured drag.

Tests with suction boundary layer control were discontinued in view of the excellent results obtained with fillet "B" without boundary layer control. Further significant reductions of drag with this fillet using boundary layer control were not anticipated since turbulent separation was not extremely evident.

DISCUSSION OF AIRSHIP FILLET INSTALLATION

Drag measurements of the fillet test project indicate that substantial drag reductions may be achieved with properly designed fillets. Airship geometry, however, restricts fillet design to some extent, especially at the trailing edge. The usual extension of an intersection by the fillet for improved pressure recovery is impractical on the airship because of the movable control surface and shape of the envelope. Furthermore, deformation of the envelope in flight requires a fillet of non-rigid construction.

A 1/4 scale model of a non-rigid fillet designed for the airship fin is illustrated in Figure 16. This is a tension-field type fillet of calendered Dacron. Fillet shape is maintained by tension of the material itself, and would be further aided by internal suction if boundary layer control were used on this type fillet.

A sketch of a proposed fillet installation is shown in Figure 17. Extension of the fillet about the leading edge of the fin would eliminate the local separation in this region, previously detected by tuft observations. Turbulent separation may possibly occur on the sharply tapered trailing edge of the fillet since extension of the intersection by the fillet is restricted. Suction boundary layer control would be required to attach the flow to the fillet trailing edge if separation did occur.

The suction system would consist of a single blower ducted to fillets on both sides of the fin with suction air being exhausted over the lower control surface as shown in the diagram. Suction could be used with either the porous Dacron material or an impervious material perforated for distributed suction. The latter case would be desirable, since a distributed suction system would be more effective. Suction requirements for the airship fillet installation must be computed from flight test measurements after installation of the fillet.

CONCLUDING REMARKS

An analysis of data from tests of the two fillets allowed the following conclusions to be made.

1. Substantial reduction of total intersection drag may be achieved with a properly designed fillet.
2. The frictional drag of a smooth fillet is small when compared to the total drag of an unfilleted intersection within a strong adverse pressure gradient.
3. Large radii near the leading edge of the fillet are undesirable since the increase in supervelocity results in a steep adverse pressure gradient which induces separation near the trailing edge.
4. Pressure recovery is improved by extending the fillet length behind the trailing edge of the intersection.
5. Fillet width should be sufficient at the trailing edge to allow the fillet to lie well within the expanding region of disturbed flow along the intersection.
6. Rounding the trailing edge of a fillet may result in poor pressure recovery.
7. Fillets requiring suction boundary layer control for prevention of separation at the trailing edge may require suction power coefficients as high as 10 per cent of the total drag coefficient of the intersection.

REFERENCES

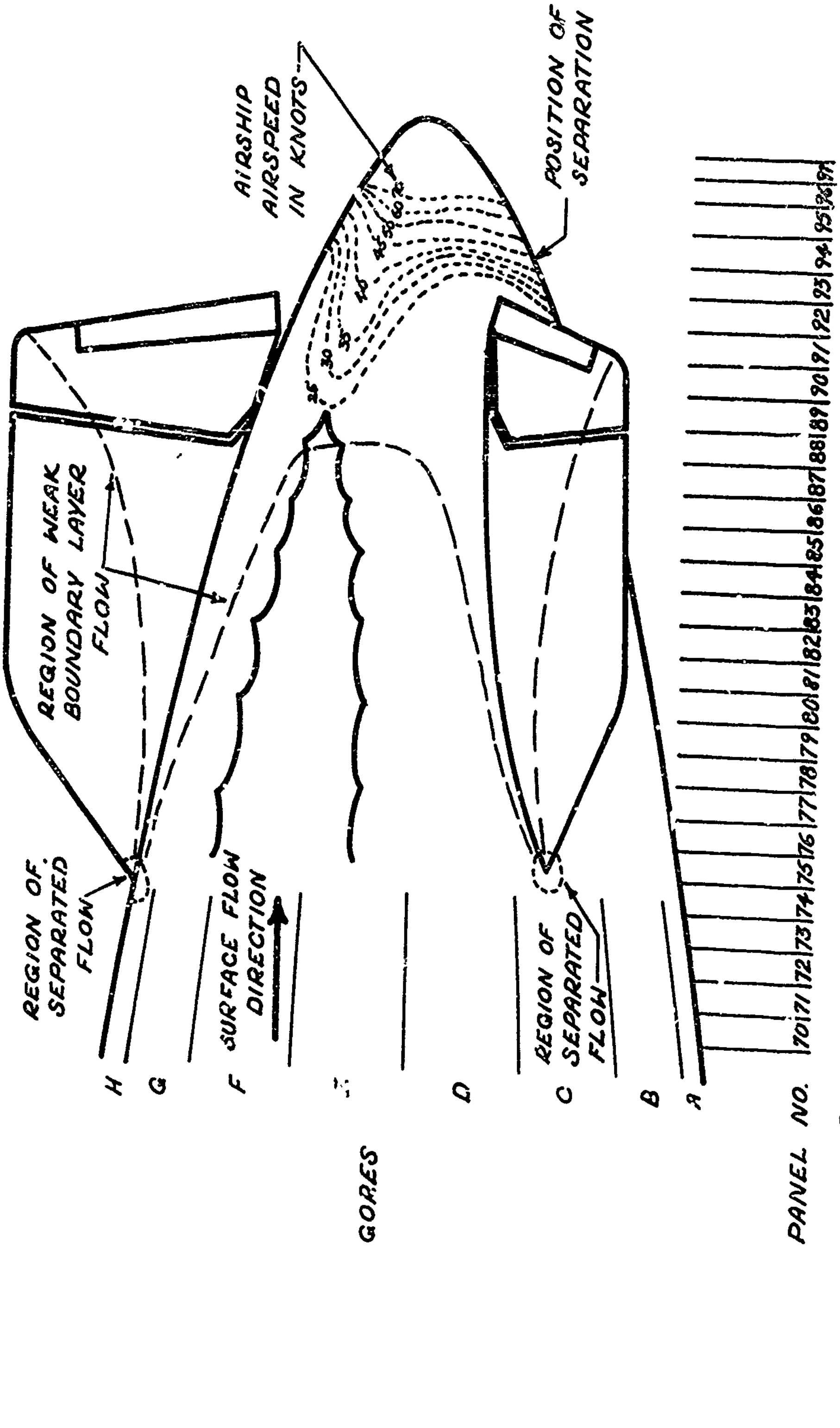
1. Cornish, J.J., III, and Boatwright, D.W., "Application of Full Scale Boundary Layer Measurements to Drag Reduction of Airships," Research Report No. 28, Aerophysics Department, Mississippi State University, 18 January 1960. (Confidential).

2. Cornish, J.J., III, and Boatwright, D.W., "Tuft Flow Studies of the ZS2G-1 Type Airship," Research Note No. 6, Aerophysics Department, Mississippi State University, 10 June 1959. (Confidential).

3. Goldstein, S., Modern Developments in Fluid Dynamics, Oxford Edition, 2 Vols., Oxford, Clarendon Press, 1938.

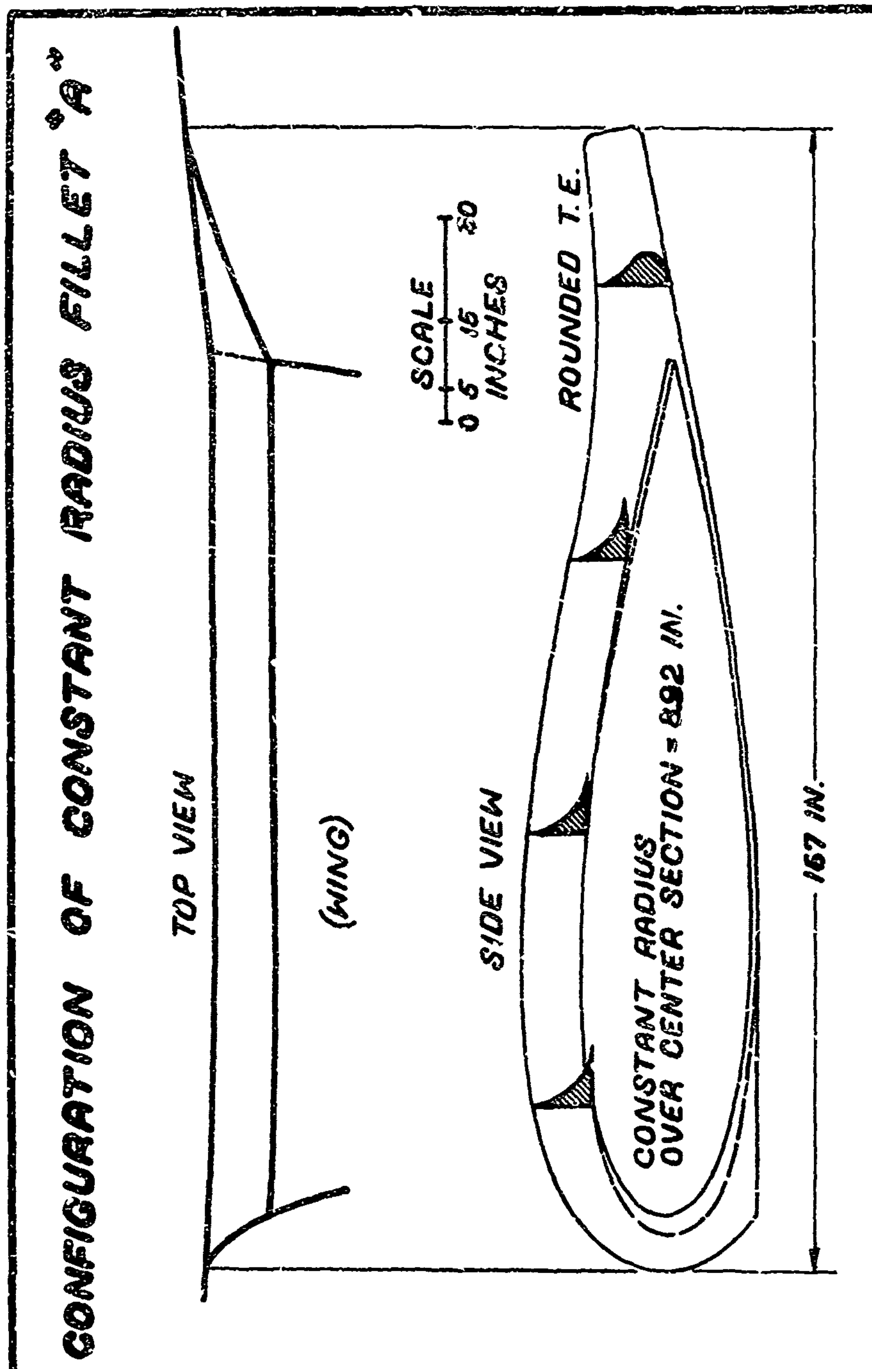
4. Raspet, A., Cornish, J.J., III, and Bryant, G.D., "Delay of the Stall by Suction Through Distributed Perforations," Aerophysics Department, Mississippi State University, January 1956.

Figure 1.



SEPARATION REGION ON ZS2G-1 AIRSHIP
STRAIGHT AND LEVEL FLIGHT

Figure 2.



CONFIGURATION OF CONSTANT RADIUS FILLET "A"
TOP VIEW
(WING)
SCALE
0 5 15 30
INCHES
ROUNDED T.E.
SIDE VIEW
CONSTANT RADIUS
OVER CENTER SECTION = 892 IN.
167 IN.

Figure 3.

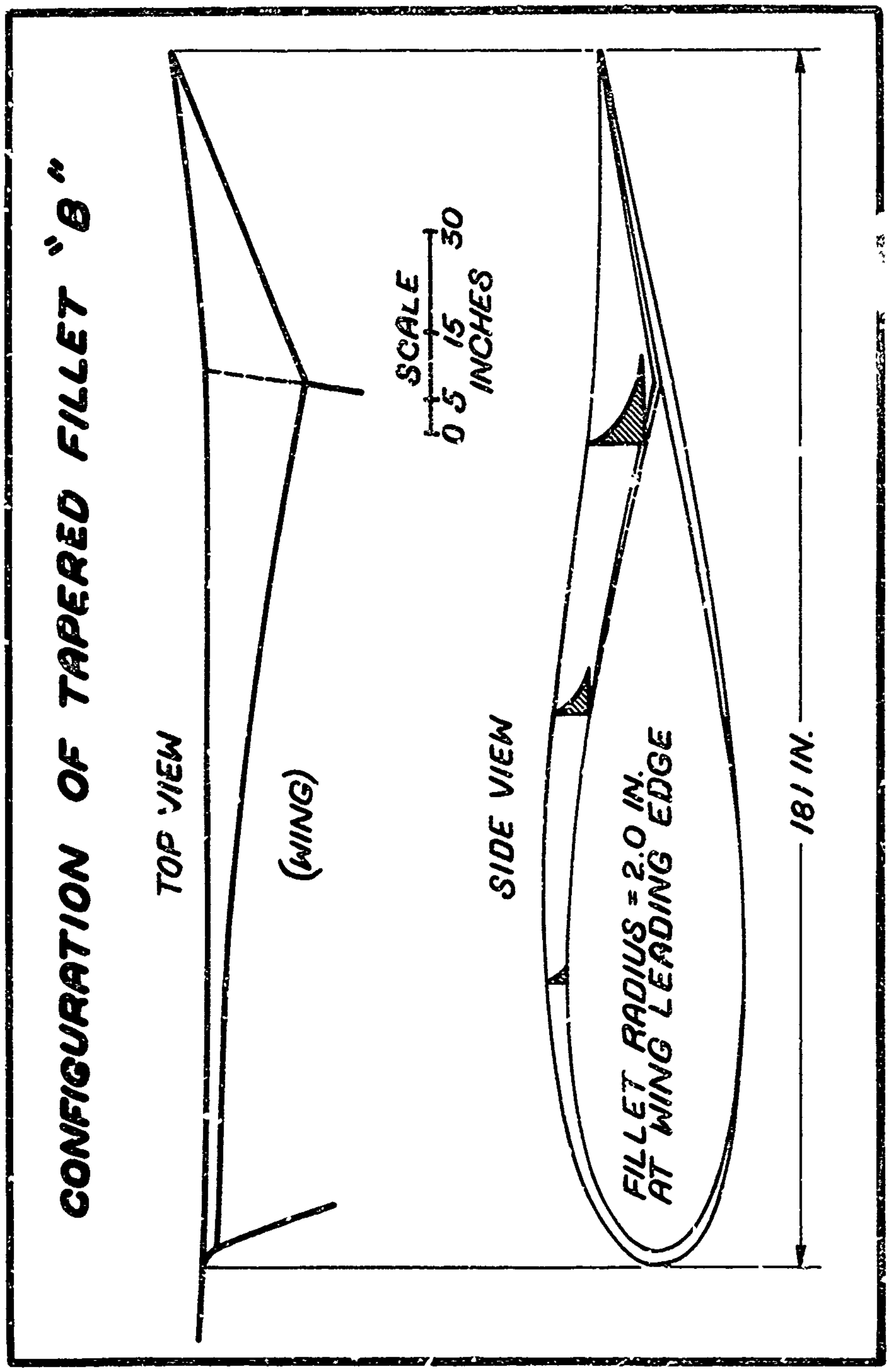
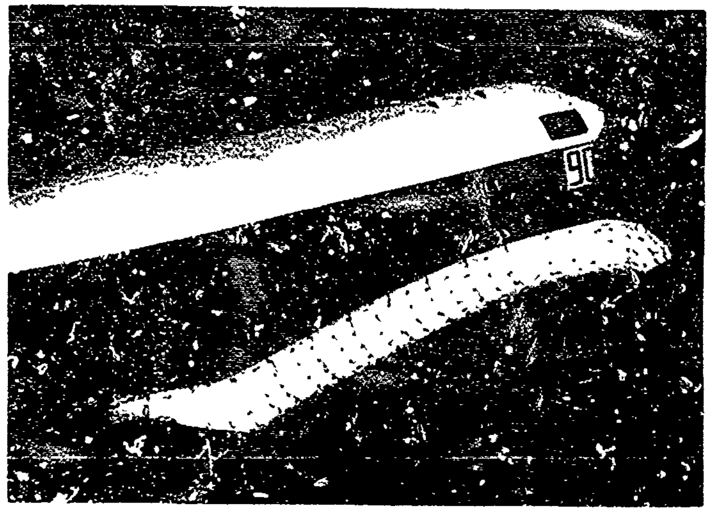
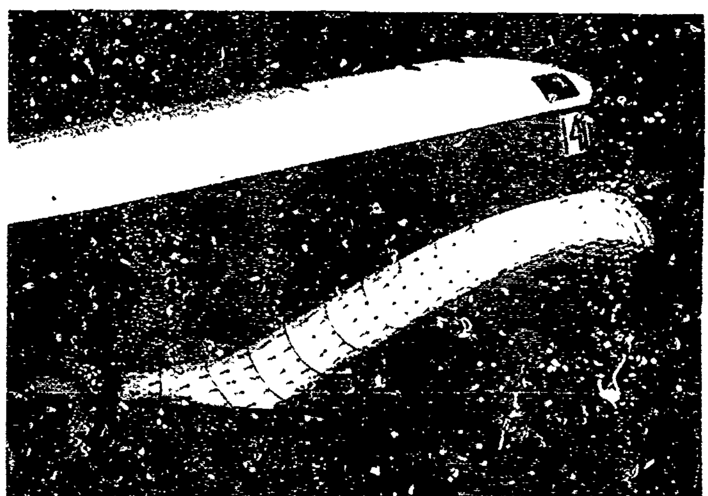

CONFIGURATION OF TAPERED FILLET "B"
TOP VIEW
(WING)
SCALE
0 5 15 30
INCHES
SIDE VIEW
FILLET RADIUS = 2.0 IN.
AT WING LEADING EDGE
181 IN.

Figure 4.

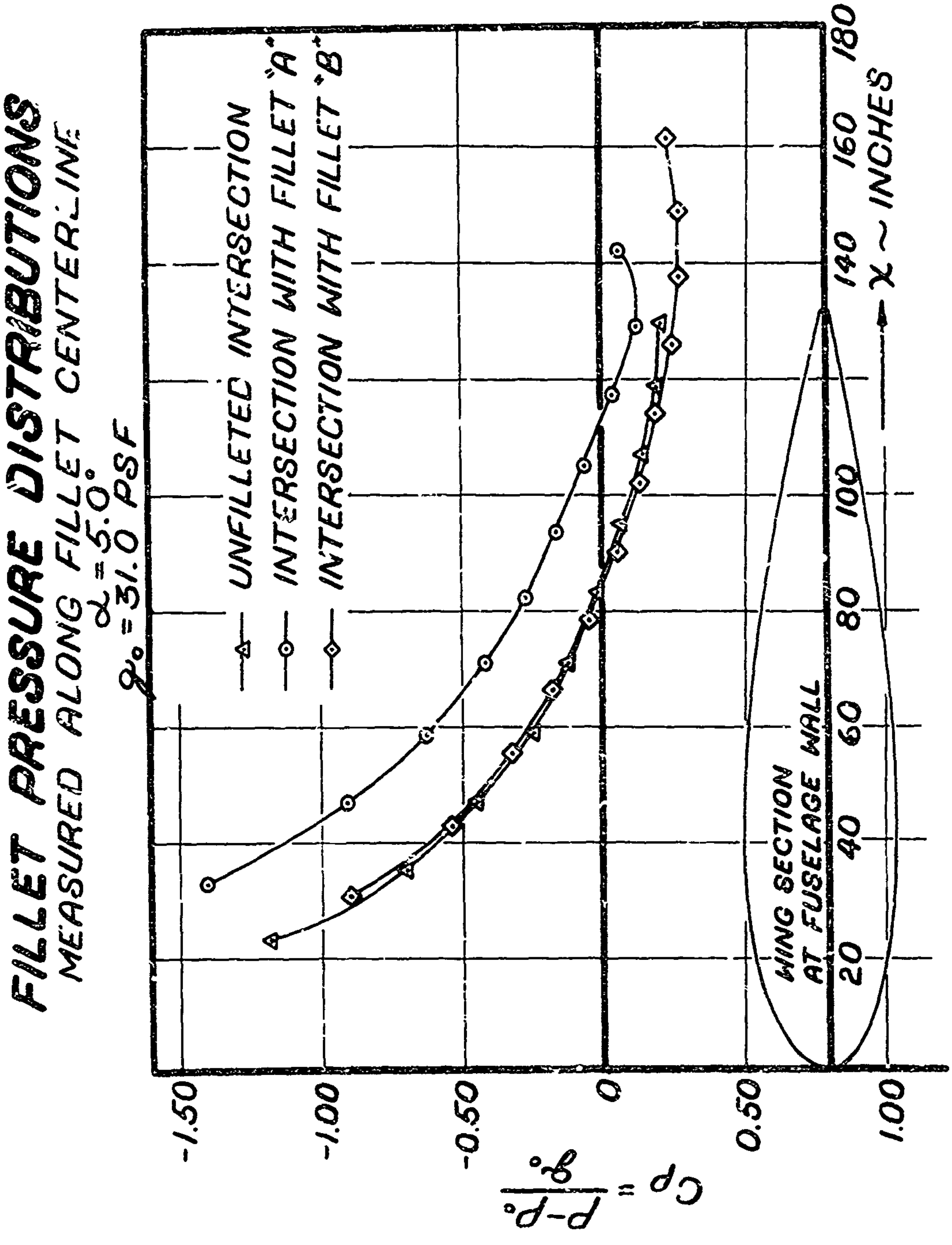


WING-ROOT SECTION WITH FILLET "A" INSTALLED. TUFTS SHOW STALLED CONDITION OF SECTION AT $\alpha = 12.0^\circ$, IAS = 90 mph



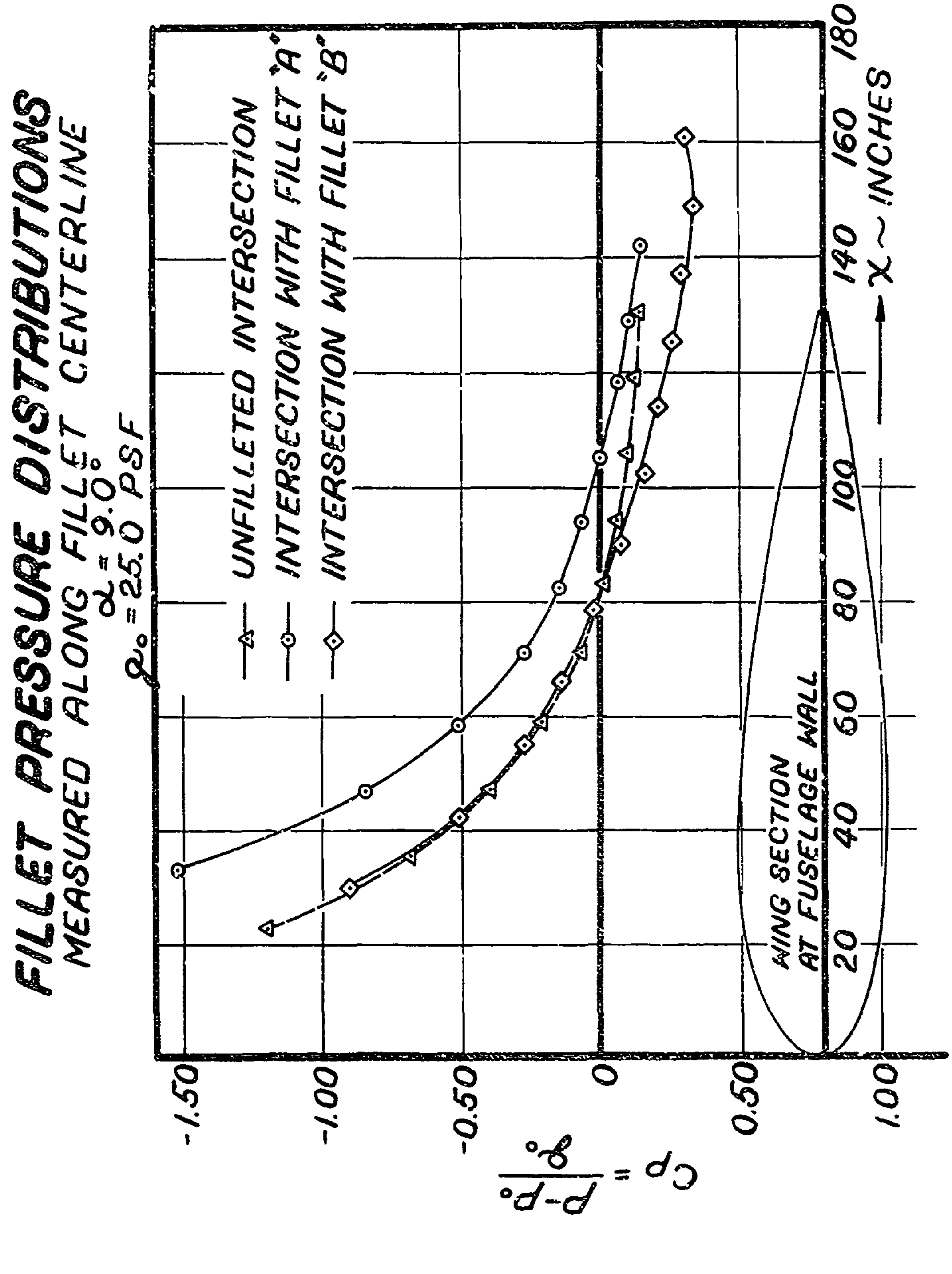
WING-ROOT SECTION AT $\alpha = 2.0^\circ$, IAS = 140 mph TUFTS SHOW FLOW PATTERN OVER FILLET WITH COMPLETELY ATTACHED FLOW.

Figure 5.



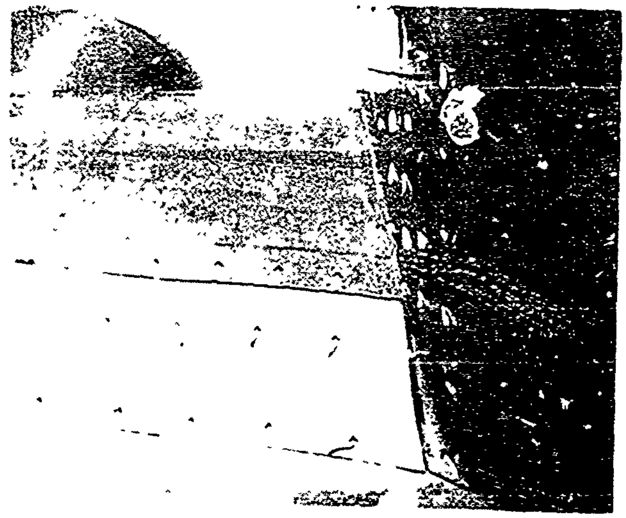
FILLET PRESSURE DISTRIBUTIONS
MEASURED ALONG FILLET CENTERLINE
α = 5.0°
q₀ = 31.0 PSF
UNFILLETED INTERSECTION
INTERSECTION WITH FILLET "A"
INTERSECTION WITH FILLET "B"
WING SECTION AT FUSELAGE WALL
20
40
60
80
100
140
160
180
X ~ INCHES
-1.50
-1.00
-0.50
0
0.50
1.00
$C_P = \frac{P - P_0}{q_0}$

Figure 6.

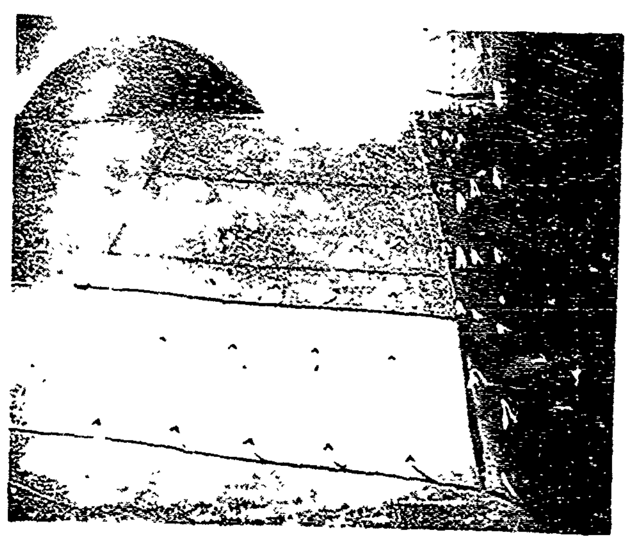


FILLET PRESSURE DISTRIBUTIONS
MEASURED ALONG FILLET CENTERLINE
α = 9.0°
q₀ = 25.0 PSF
UNFILLETED INTERSECTION
INTERSECTION WITH FILLET "A"
INTERSECTION WITH FILLET "B"
WING SECTION
AT FUSELAGE WALL
20
40
60
80
100
140
160
180
X ~ INCHES
-1.50
-1.00
-0.50
0
0.50
1.00
Cp = (P-P₀)/q₀

Figure 7.



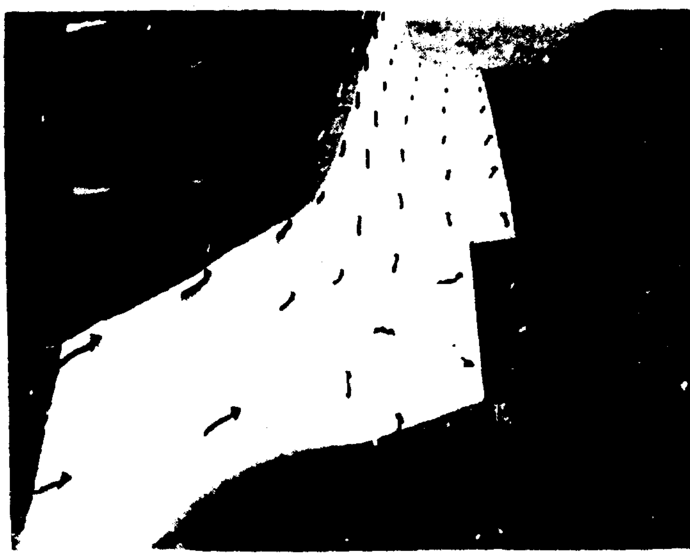
WING-FUSELAGE INTERSECTION
$\alpha = 5.0^\circ$, IAS = 115 mph



WING-FUSELAGE INTERSECTION
$\alpha = 9.0^\circ$, IAS = 101 mph

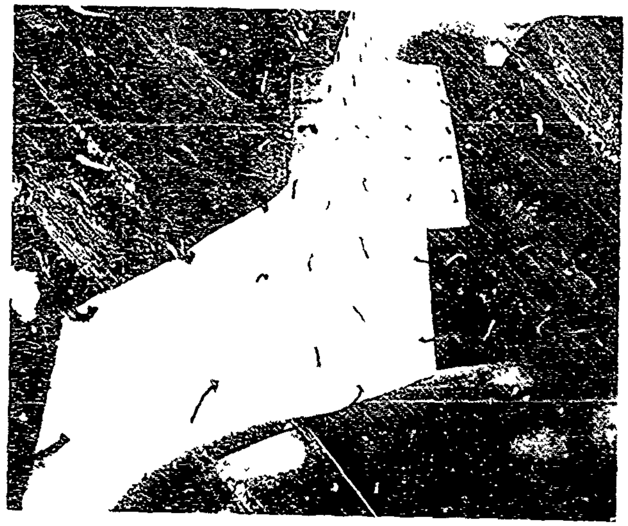
Figure 8.

FILLET "A" WITHOUT BLC
$\alpha = 5.0°$, IAS = 119 mph



FILLET "A" WITH BLC
$\alpha = 5.0°$, IAS = 119 mph

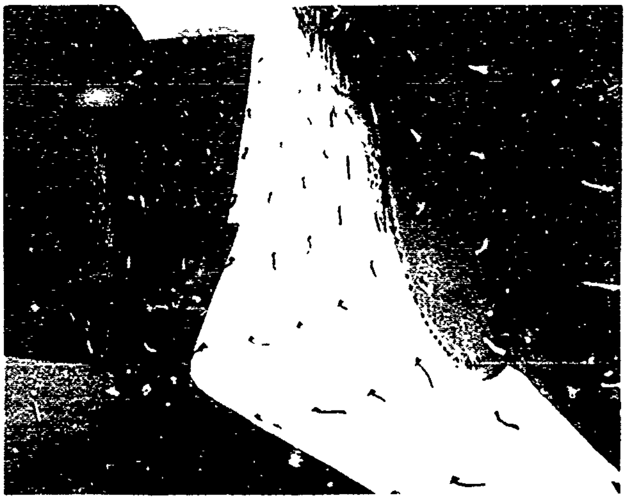
Figure 9.



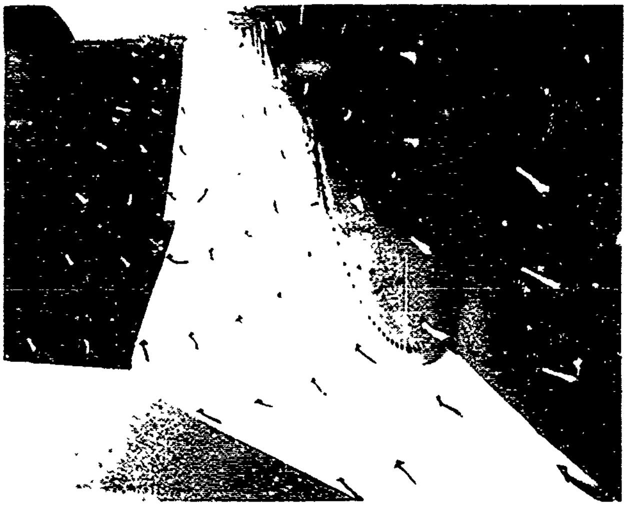
FILLET "A" WITHOUT BLC
$\alpha = 9.0°$; IAS = 102 mph

FILLET "A" WITH BLC
$\alpha = 9.0°$, IAS = 102 mph

Figure 10.



FILLET "B"
$\alpha = 5\ 0°$, IAS = 115 mph



FILLET "B"
$\alpha = 14.5°$, IAS = 101 mph

Figure 11.

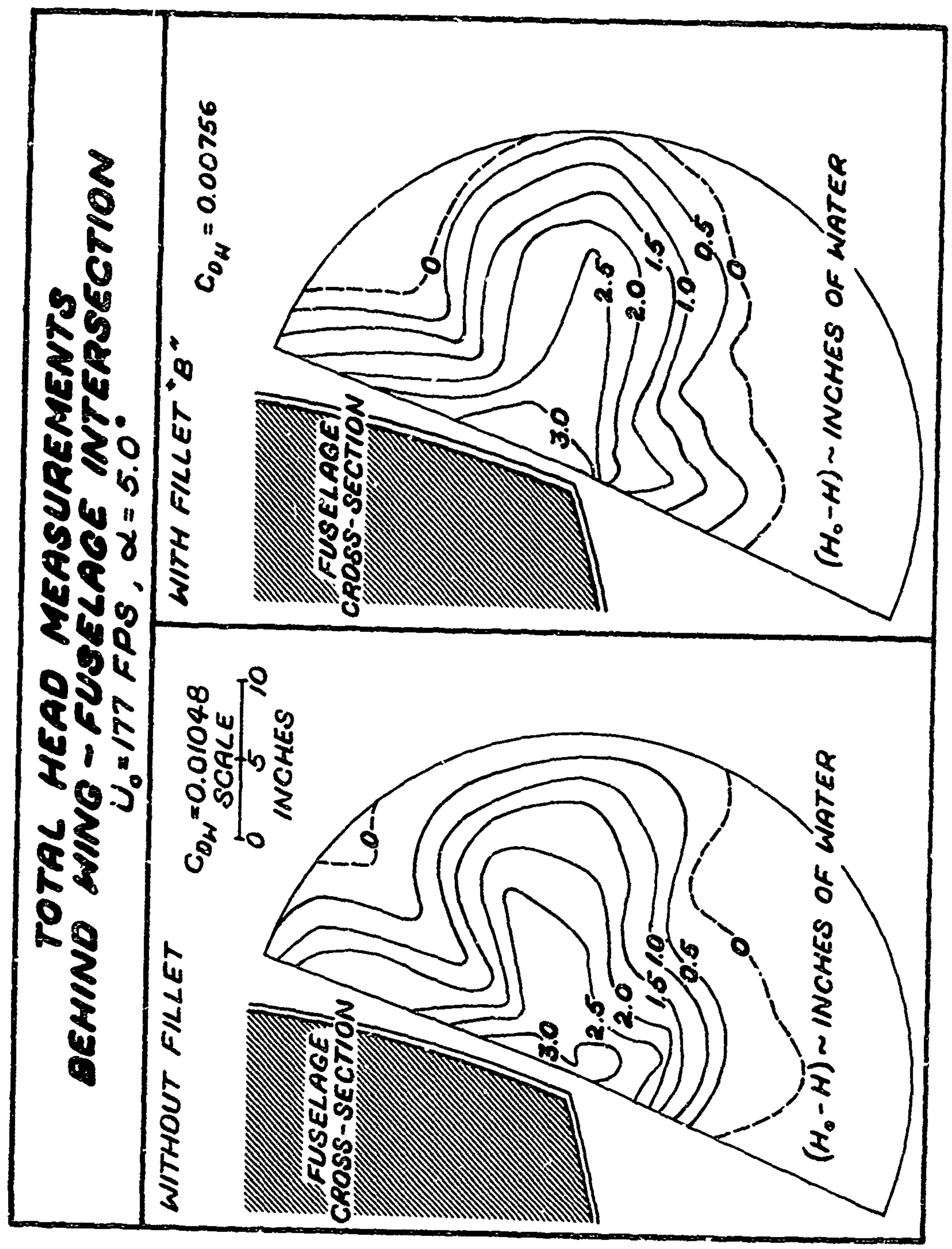
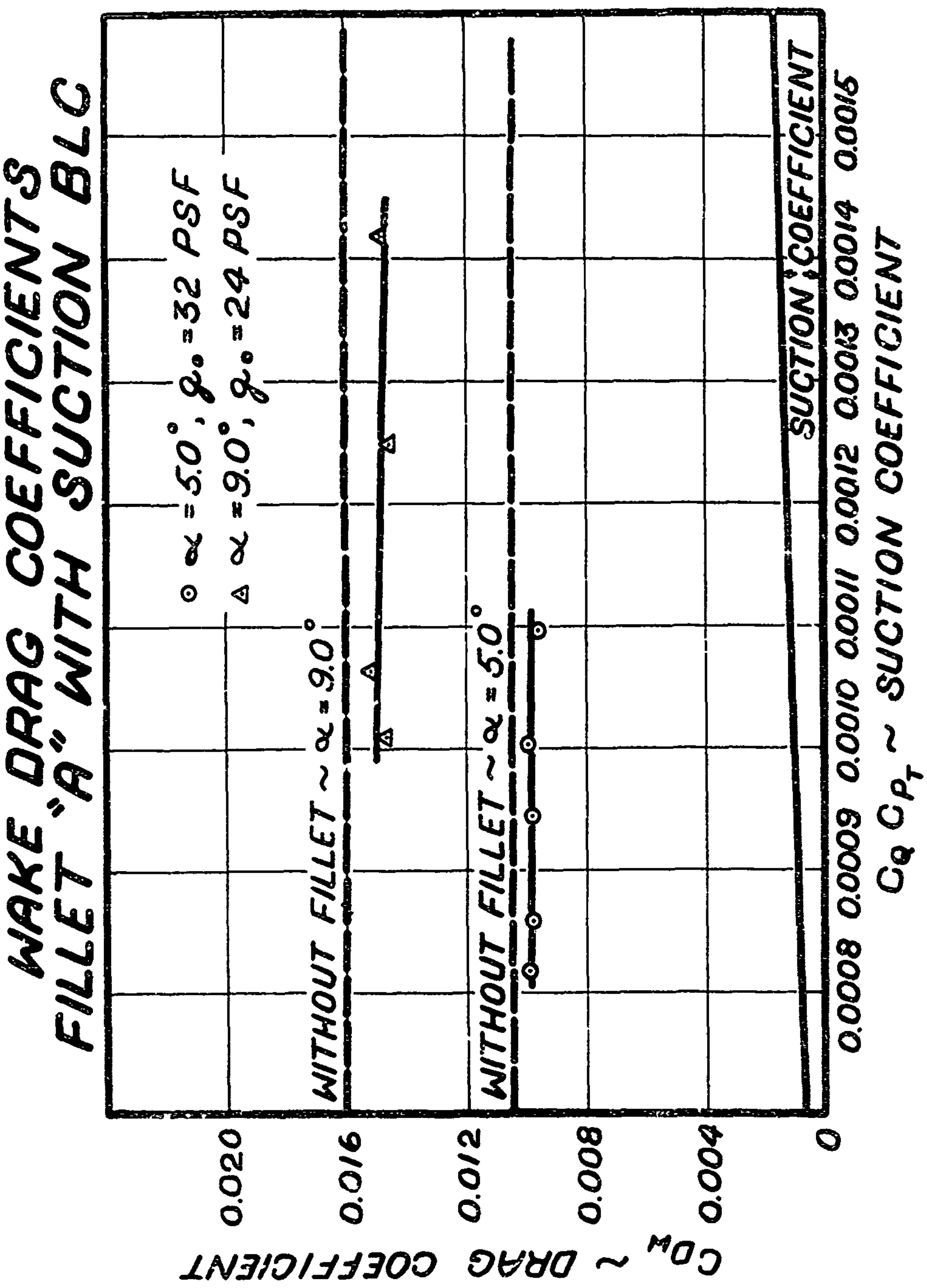
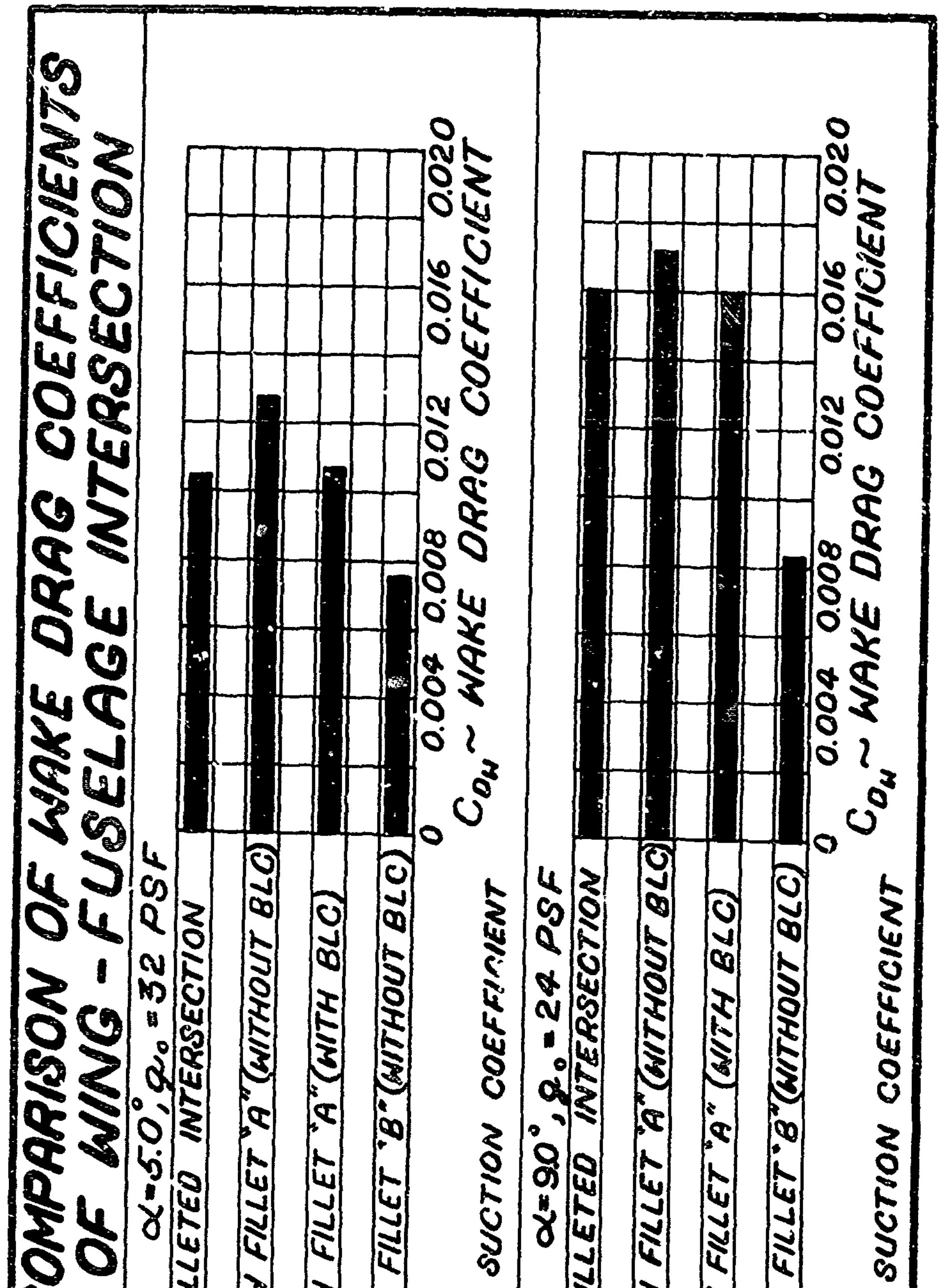

TOTAL HEAD MEASUREMENTS
BEHIND WING - FUSELAGE INTERSECTION
U_o = 177 FPS , α = 5.0°
WITHOUT FILLET
C_{D_W} = 0.01048
SCALE
0 5 10
INCHES
FUSELAGE CROSS-SECTION
0
3.0
2.5
2.0
1.5
1.0
0.5
0
$(H_o - H)$ ~ INCHES OF WATER
WITH FILLET "B"
C_{D_W} = 0.00756
FUSELAGE CROSS-SECTION
0
3.0
2.5
2.0
1.5
1.0
0.5
0
$(H_o - H)$ ~ INCHES OF WATER

Figure 12.



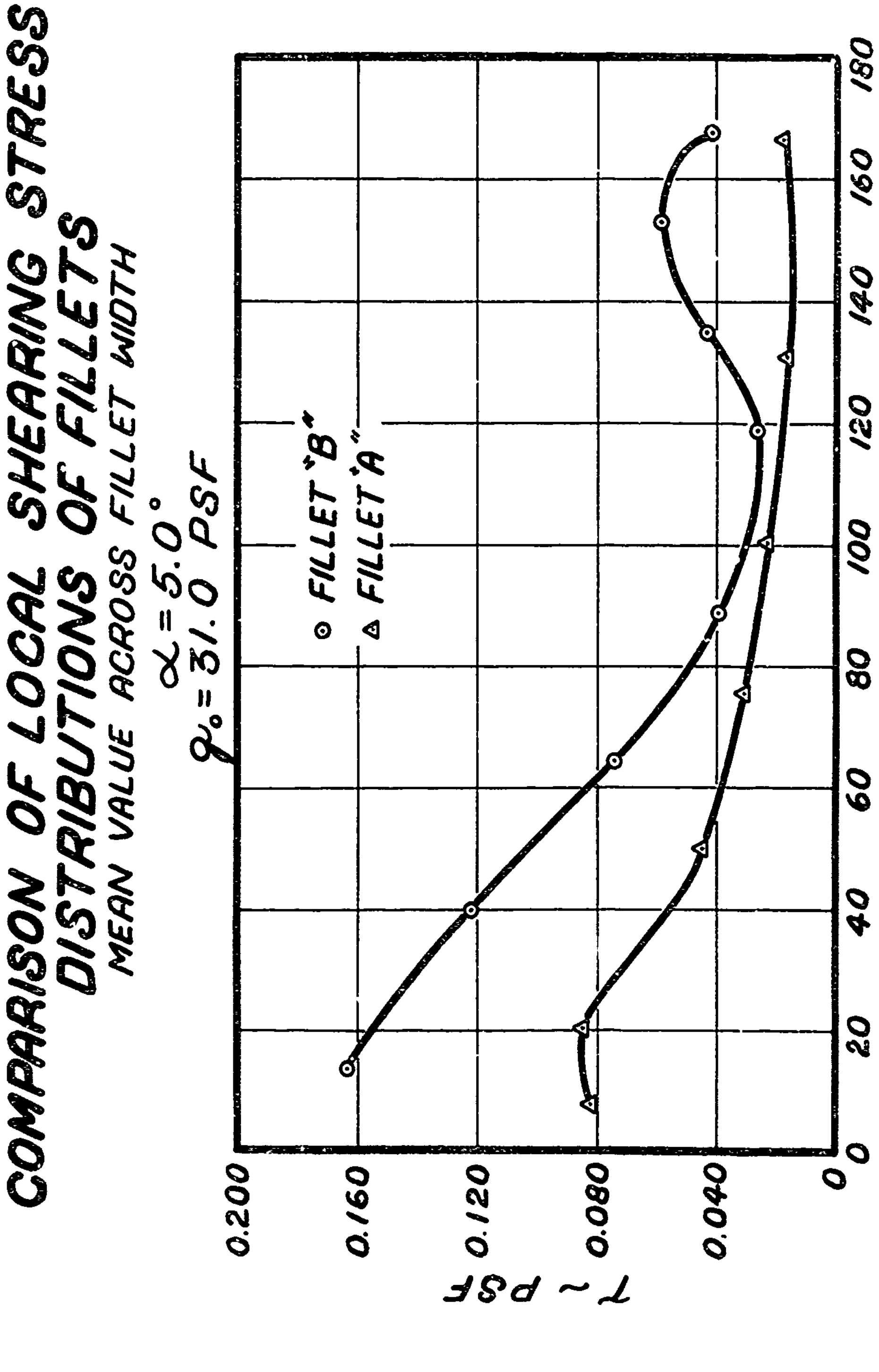
WAKE DRAG COEFFICIENTS
FILLET "A" WITH SUCTION BLC
⊙ α = 5.0°, q_o = 32 PSF
△ α = 9.0°, q_o = 24 PSF
WITHOUT FILLET ~ α = 9.0°
WITHOUT FILLET ~ α = 5.0°
SUCTION COEFFICIENT
0.0008 0.0009 0.0010 0.0011 0.0012 0.0013 0.0014 0.0015
$C_Q C_{P_T}$ ~ SUCTION COEFFICIENT
0 0.004 0.008 0.012 0.016 0.020
C_{D_W} ~ DRAG COEFFICIENT

Figure 13.



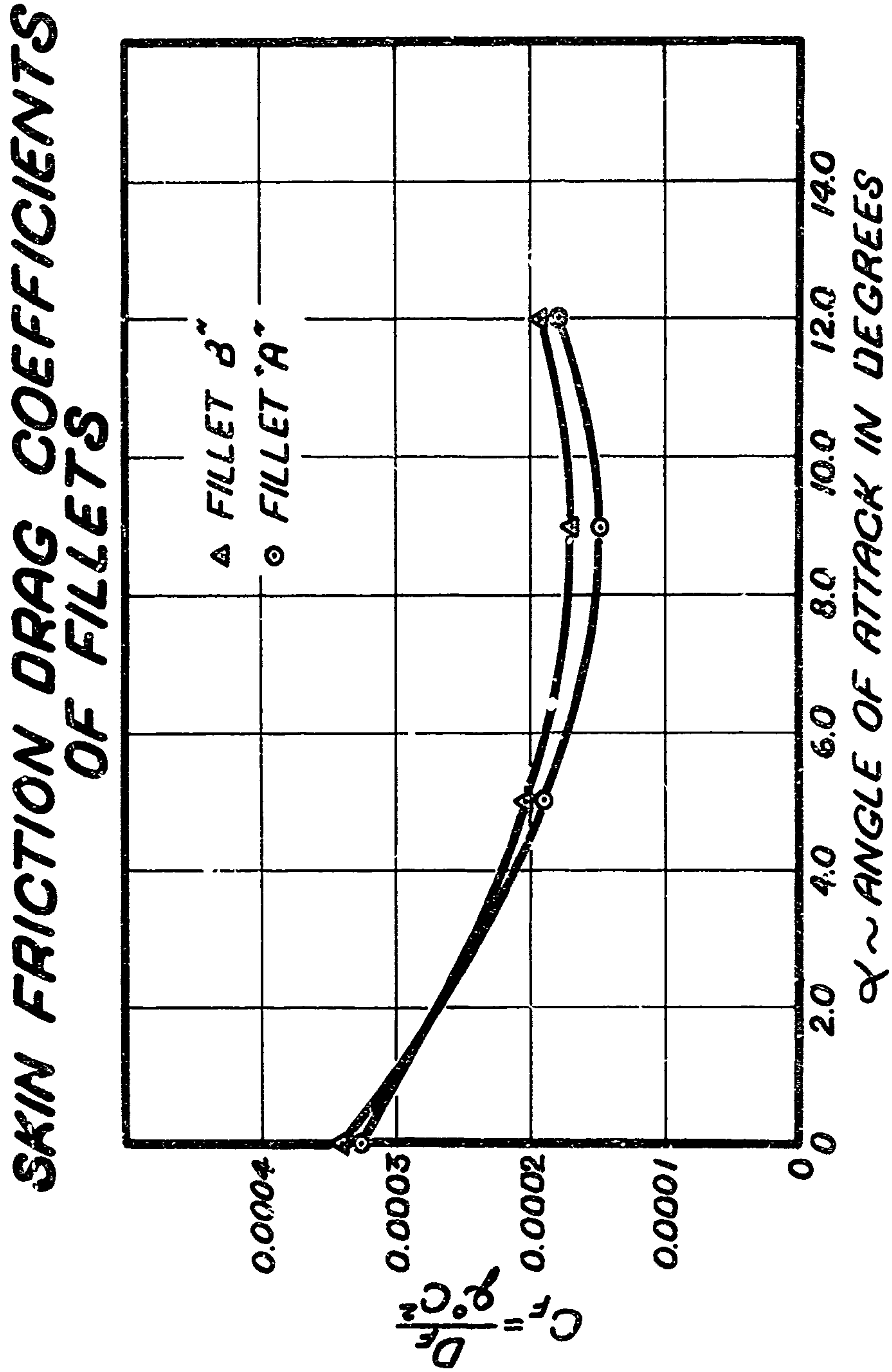
COMPARISON OF WAKE DRAG COEFFICIENTS
OF WING - FUSELAGE INTERSECTION
$\alpha = 5.0°, q_0 = 32$ PSF
UNFILLETED INTERSECTION
WITH FILLET "A" (WITHOUT BLC)
WITH FILLET "A" (WITH BLC)
WITH FILLET "B" (WITHOUT BLC)
SUCTION COEFFICIENT
0 0.004 0.008 0.012 0.016 0.020
C_{D_W} ~ WAKE DRAG COEFFICIENT
$\alpha = 9.0°, q_0 = 24$ PSF
UNFILLETED INTERSECTION
WITH FILLET "A" (WITHOUT BLC)
WITH FILLET "A" (WITH BLC)
WITH FILLET "B" (WITHOUT BLC)
SUCTION COEFFICIENT
0 0.004 0.008 0.012 0.016 0.020
C_{D_W} ~ WAKE DRAG COEFFICIENT

Figure 14.



COMPARISON OF LOCAL SHEARING STRESS DISTRIBUTIONS OF FILLETS
MEAN VALUE ACROSS FILLET WIDTH
$\alpha = 5.0°$
$q_o = 31.0$ PSF
FILLET "B"
FILLET "A"
τ ~ PSF
0.200
0.160
0.120
0.080
0.040
0
0
20
40
60
80
100
120
140
160
180
X ~ INCHES

Figure 15.

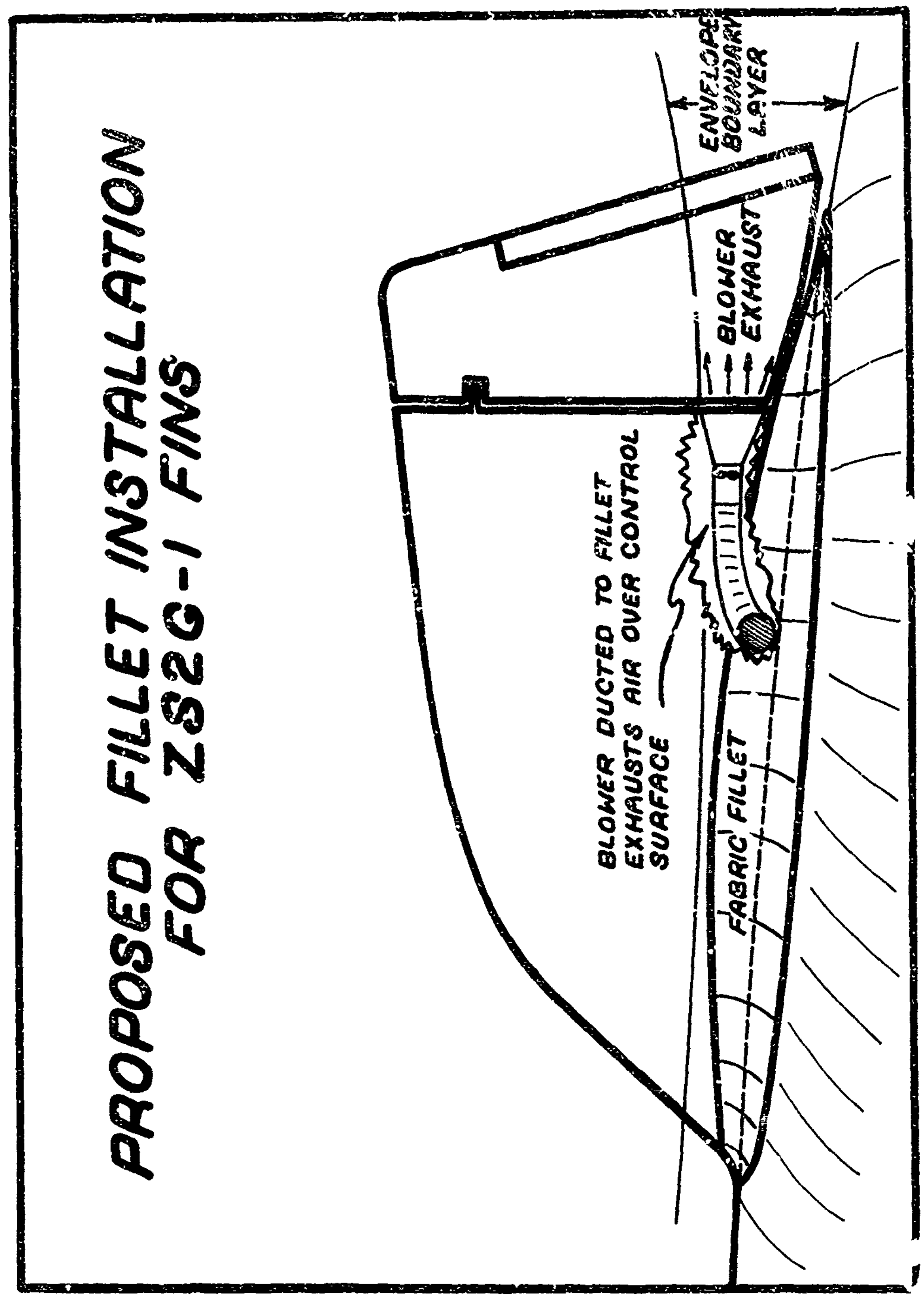


SKIN FRICTION DRAG COEFFICIENTS OF FILLETS
FILLET "B"
FILLET "A"
α ~ ANGLE OF ATTACK IN DEGREES
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0.0
0.0001
0.0002
0.0003
0.0004
$C_F = \frac{D_F}{\rho_0 C^2}$

Figure 16.

MODEL OF FABRIC TENSION-FIELD FILLET
$\frac{1}{2}$ SIZE SCALE

Figure 17.


PROPOSED FILLET INSTALLATION
FOR ZS2G-1 FINS
ENVELOPE BOUNDARY LAYER
BLOWER EXHAUST
BLOWER DUCTED TO FILLET
EXHAUSTS AIR OVER CONTROL
SURFACE
FABRIC FILLET